

High Temperature Water-Titanium Heat Pipe Radiators for the Kilopower Fission Power System

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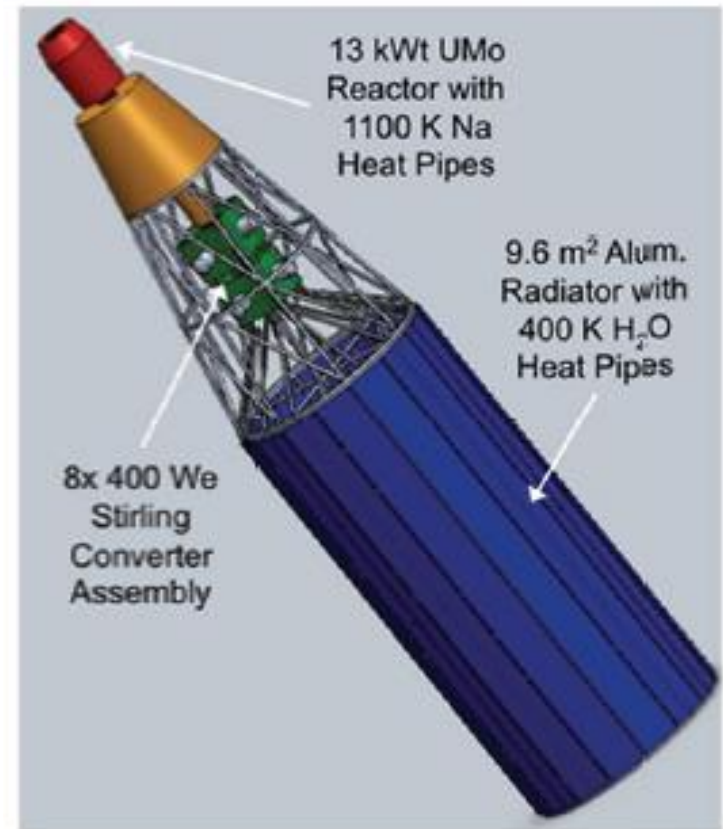


Outline



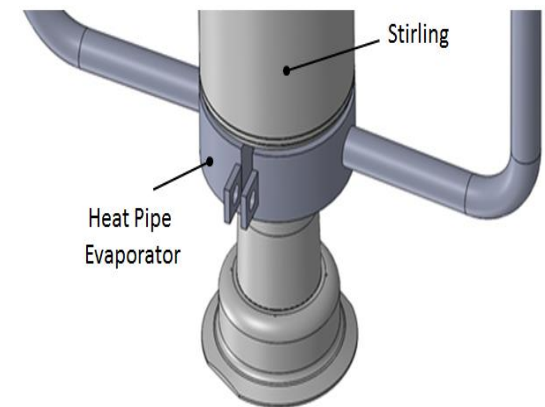
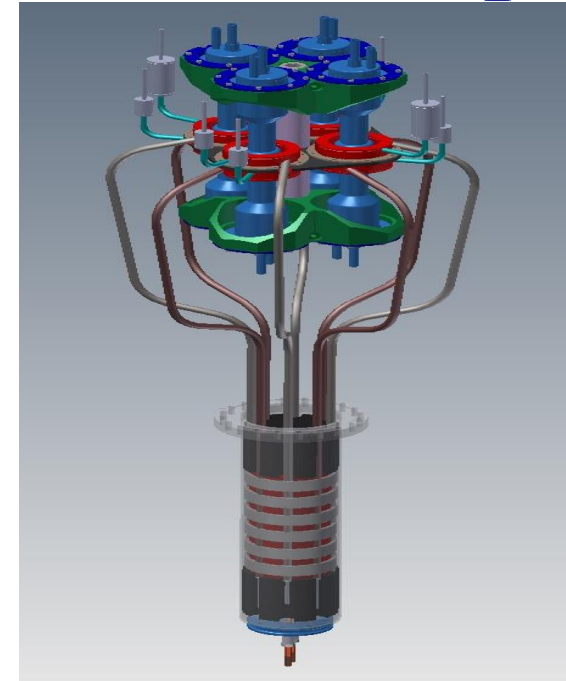
- Motivation
- Objectives
- Evaporator Design, Fabrication, and Testing
- Radiator Trade Study
- S-Bonded Radiator Fabrication and Testing
- Key Results & Future Work
- Acknowledgements

- NASA Glenn is examining small fission reactors for future space transportation and surface power applications
 - These Kilopower reactors would have an 8 to 15 year design life that could be available for a 2020 launch to support future NASA science missions
 - Both 1 kWe thermoelectric and 3 kWe Stirling systems have been examined
- Titanium-Water heat pipes have been proposed to transport the waste heat from the Stirling converters to the system radiator



Mason, Gibson, and Poston, 2013

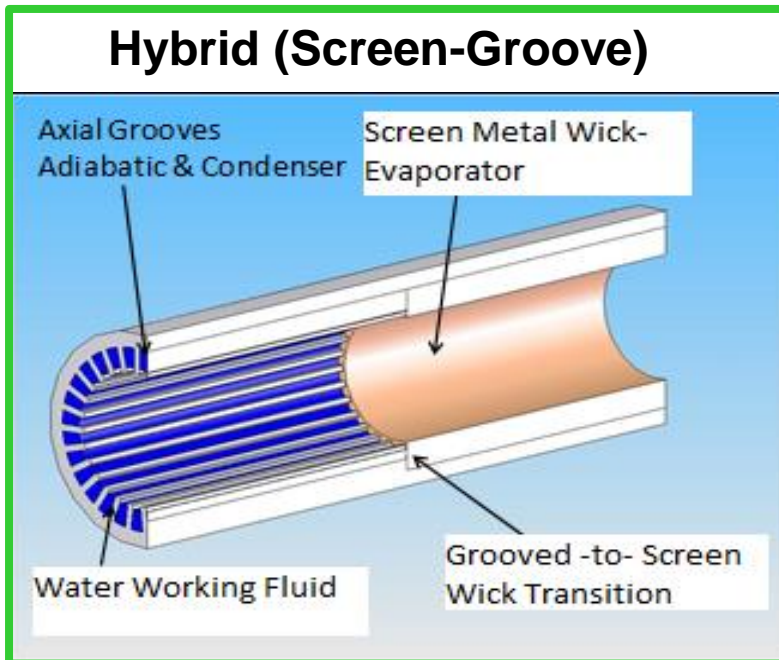
- ◆ **Overall objective**: develop full-length titanium water heat pipes for testing with the Stirling convertors on the Kilopower demonstration unit
 - Four Heat pipes/Two Stirling convertors
- ◆ **Sub-objectives**:
 - Design the heat pipe evaporator to interface with the cold end of the Stirling convertor
 - Design the radiator
 - Extensive freeze/thaw testing
 - Fabricate 4 heat pipes with radiator fins
 - **Testing of heat pipes at ACT, followed by NASA Glenn**
 - Design of prototypic ISS experiment
 - **Additional heat pipe for shock and vibration tests**



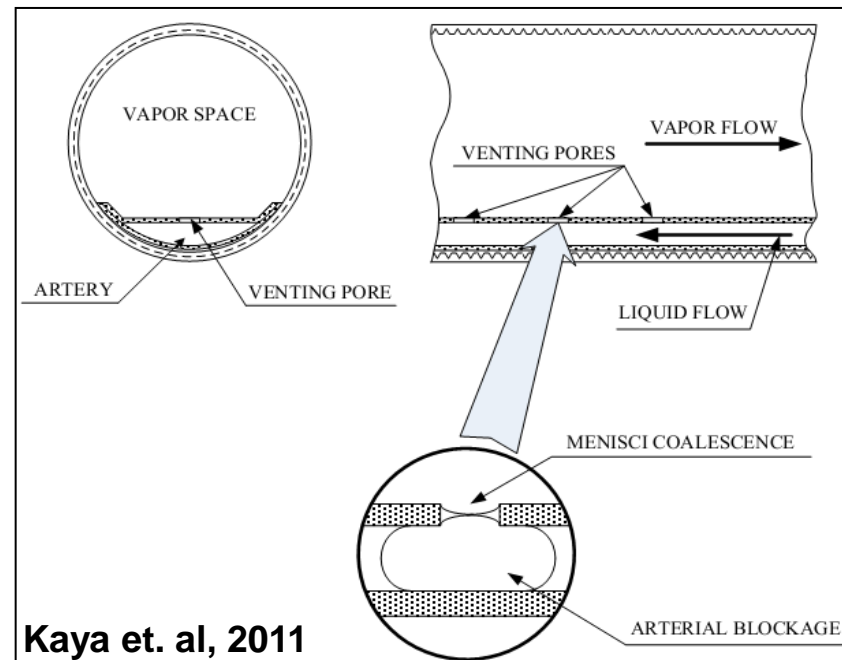
- ◆ **Wick must accommodate four operating conditions:**
 - ◆ Space: Zero gravity; capillary forces must drive liquid return to evaporator
 - ◆ Earth, Slightly adverse: 0.1" – 0.3" evaporator superior to condenser
 - ◆ Earth, Gravity Aided: Fluid returned to evap. by gravity (thermosiphon)
 - ◆ Launch: Evaporator is superior to condenser; wick deprimes

Suitable Wick Structures

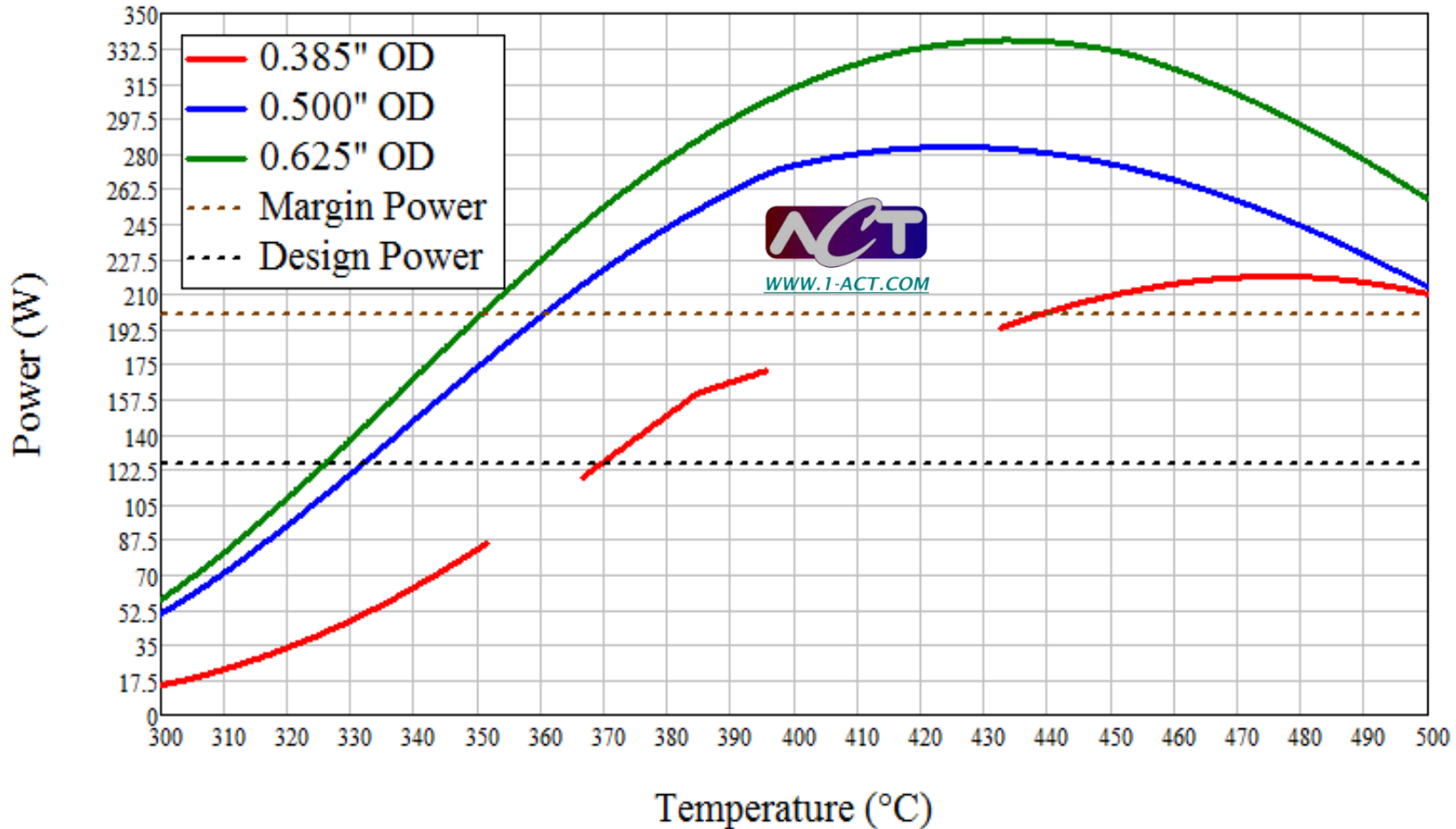
Hybrid (Screen-Groove)



Self-Venting Arterial

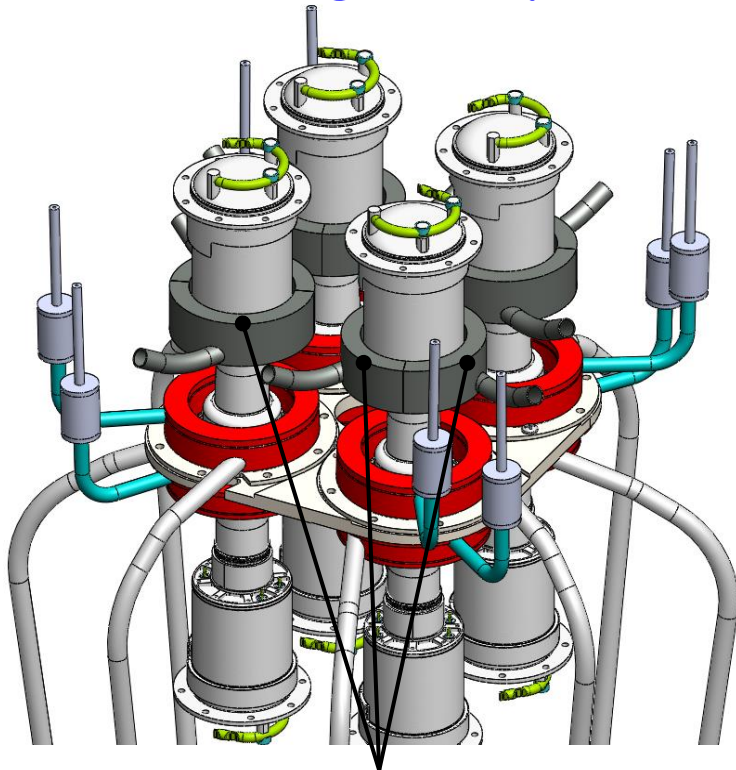


Performance Predictions for a xin OD, 67" Long Hybrid Heat Pipe



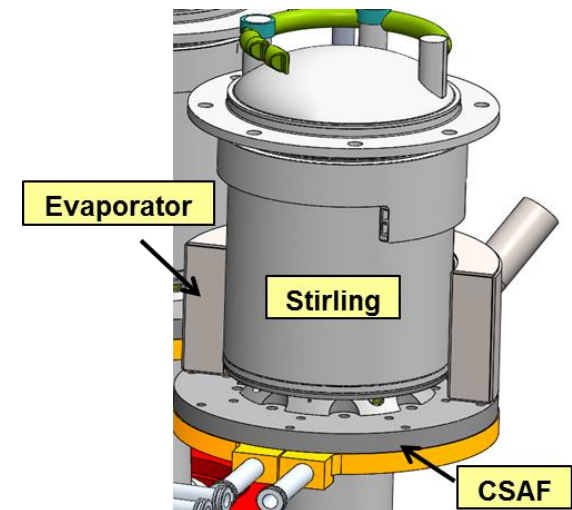
◆ 0.5" outer diameter hybrid (screen-groove) heat pipe was selected

View of Stirling engines and thermal management system



(Stirling cold end heat pipe evaporators colored dark grey)

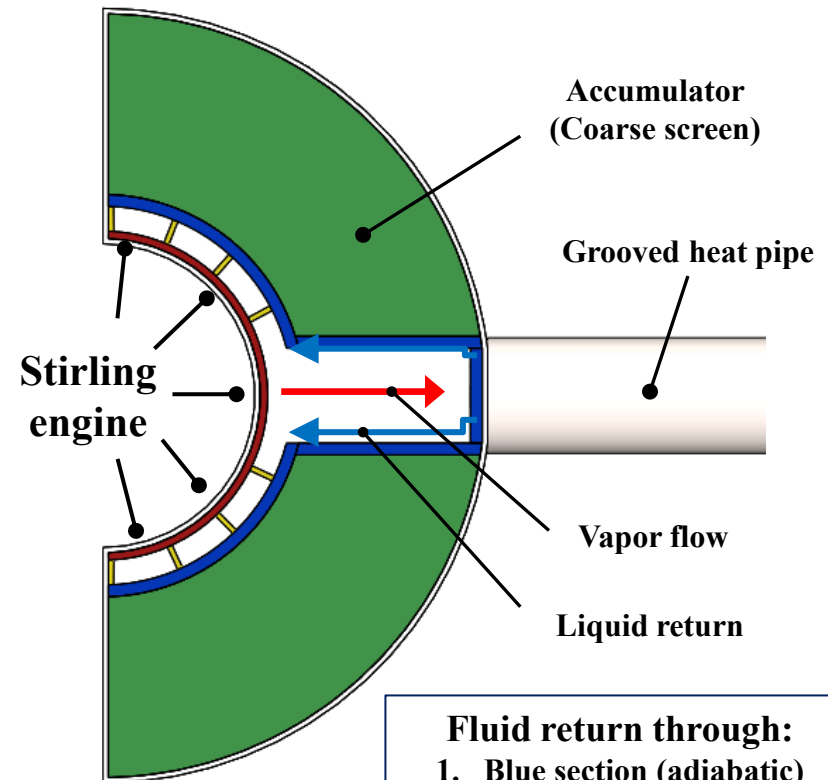
- ◆ The cold end of the Stirling engine is connected to the radiator panels via titanium water heat pipes
 - In order to prevent damage from freezing of the working fluid in the heat pipe grooves, an accumulator will be used to contain the fluid
 - The heat pipes will mount to CSAF instead of directly to the Stirling
 - Additionally, the heat pipes will be tested with an annular heater block (inner diameter surface of evaporator)



◆ Dynamics of working fluid

- $r_{c_{fine_screen}} < r_{c_{coarse_screen}} < r_{c_{grooves}}$
- At the interface of the grooved heat pipe and evaporator, only the fine screen is in contact with the grooves.
- This ensures that coarse screen (accumulator) fills with fluid only when the fine screen is saturated and there is no heat applied to the evaporator.
- Therefore the accumulator only fills with fluid when the heat pipe is not in operation

Common fluid return for all configurations

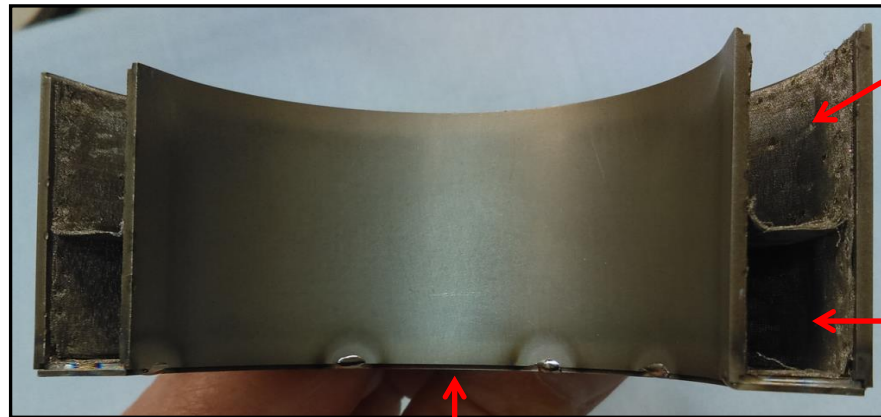


Fluid return through:

1. Blue section (adiabatic)
 2. Yellow section (bridges)
 3. Red section (evaporator)
- (Note: all are of fine screen)

Evaporator Fabrication (CSAF)

- The evaporator is a weldment where each piece is screened individually



Accumulator
To be filled with
100 size mesh

Vapor Space
Lined with 150
size mesh

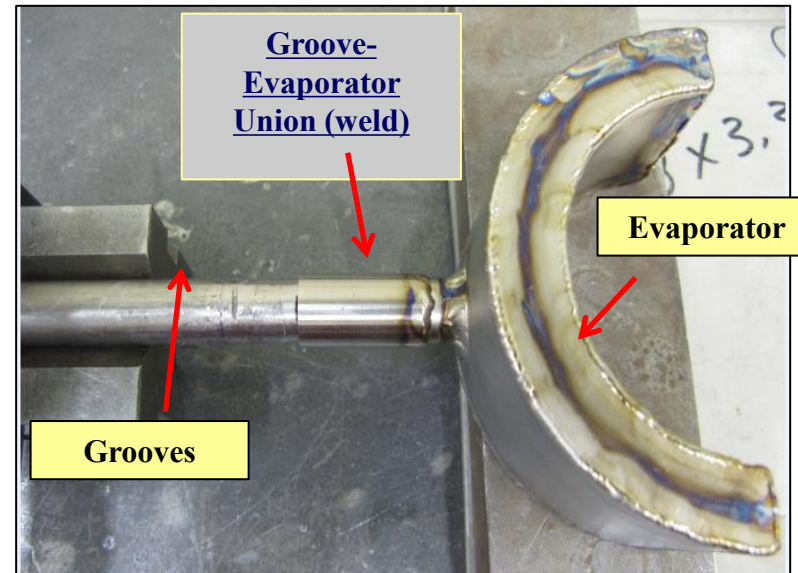
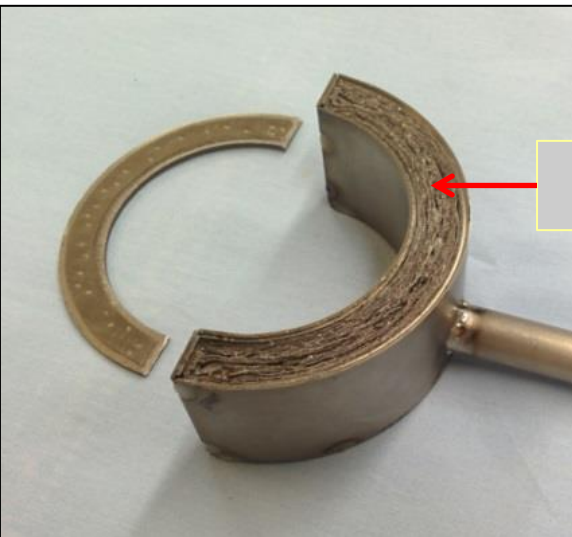
Heat Input
Surface

Accumulator

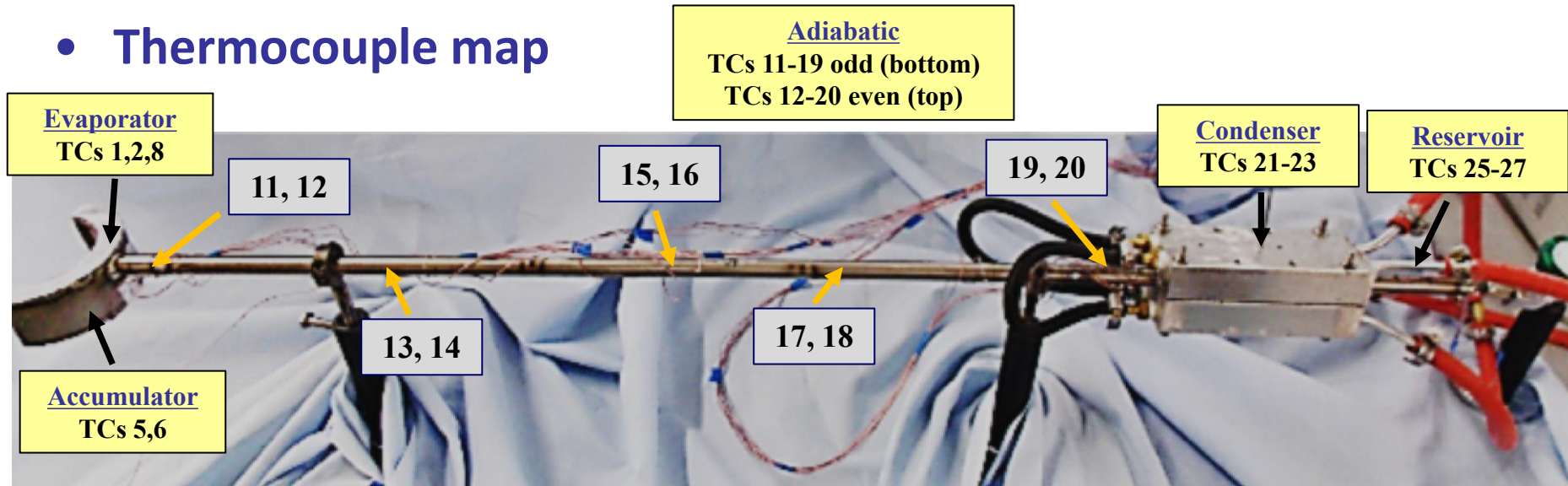
Groove-
Evaporator
Union (weld)

Evaporator

Grooves



- Thermocouple map



- Test details

- Grooved heat pipe (from Phase I) length: 34" (reservoir , condenser, adiabatic)
- Condenser length: 5"
- NCG Reservoir length: 3"
- Heater block only applies heat to the evaporator (not the accumulator)
- Accumulator is inferior to the evaporator for all test cases

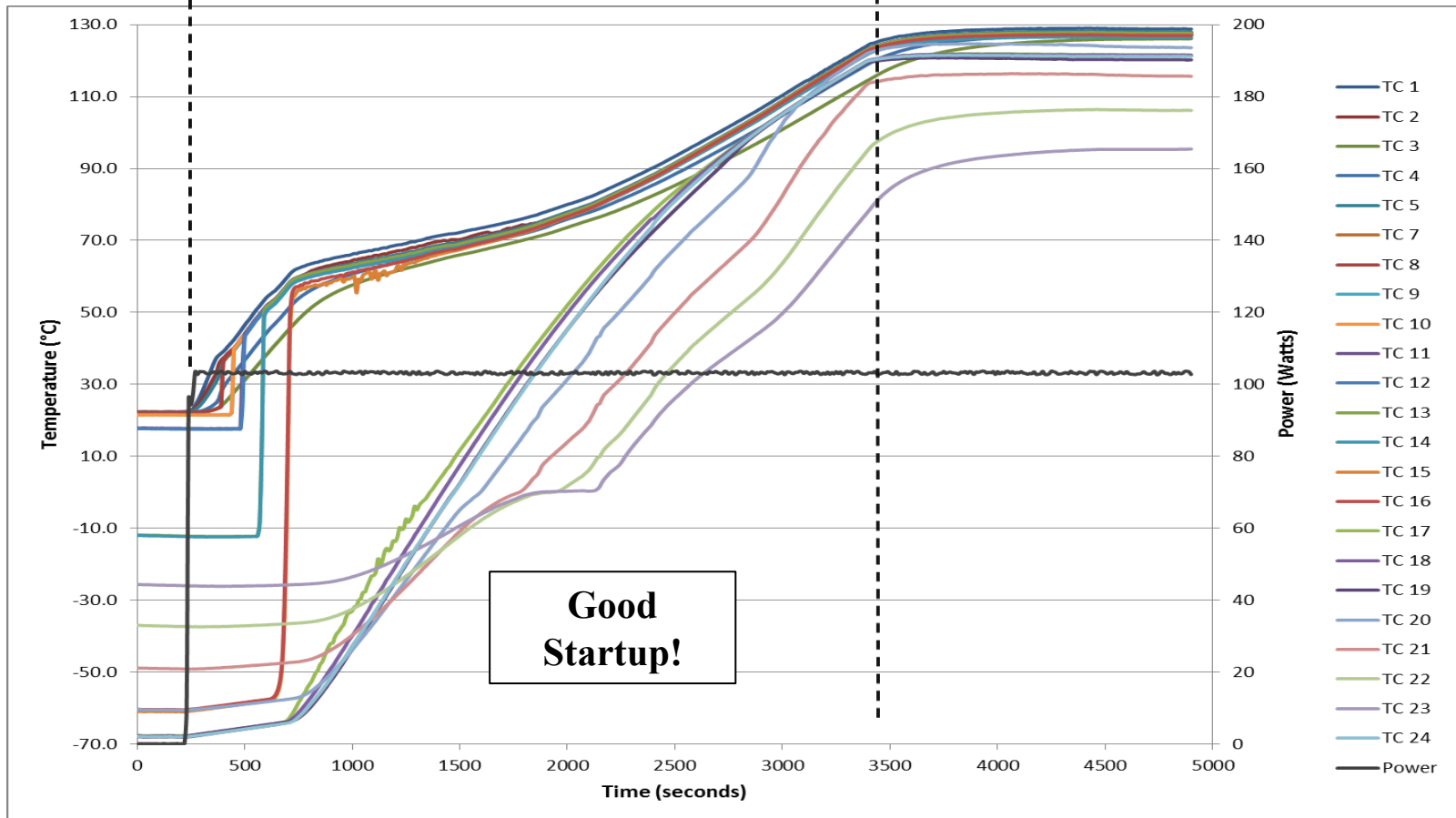
Freeze-Thaw Startup Test

- The condenser was cooled to -70°C and a step input of 100 Watts was applied
- Active cooling was suspended until heat pipe reached operating temp. of 120°C

Frozen (-70°C)
Active Cooling

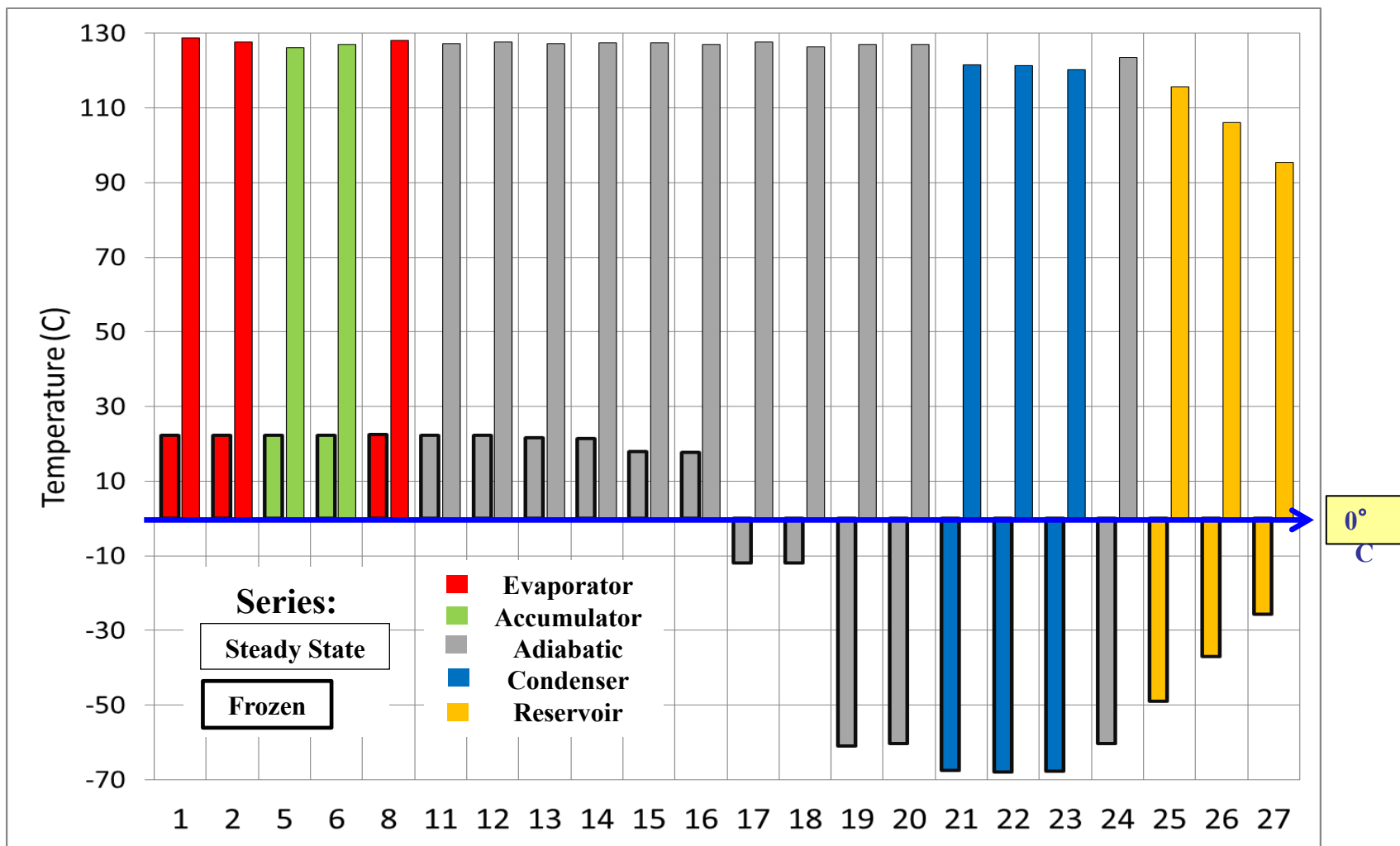
Startup
No Cooling

Steady State (120°C)
Active Cooling

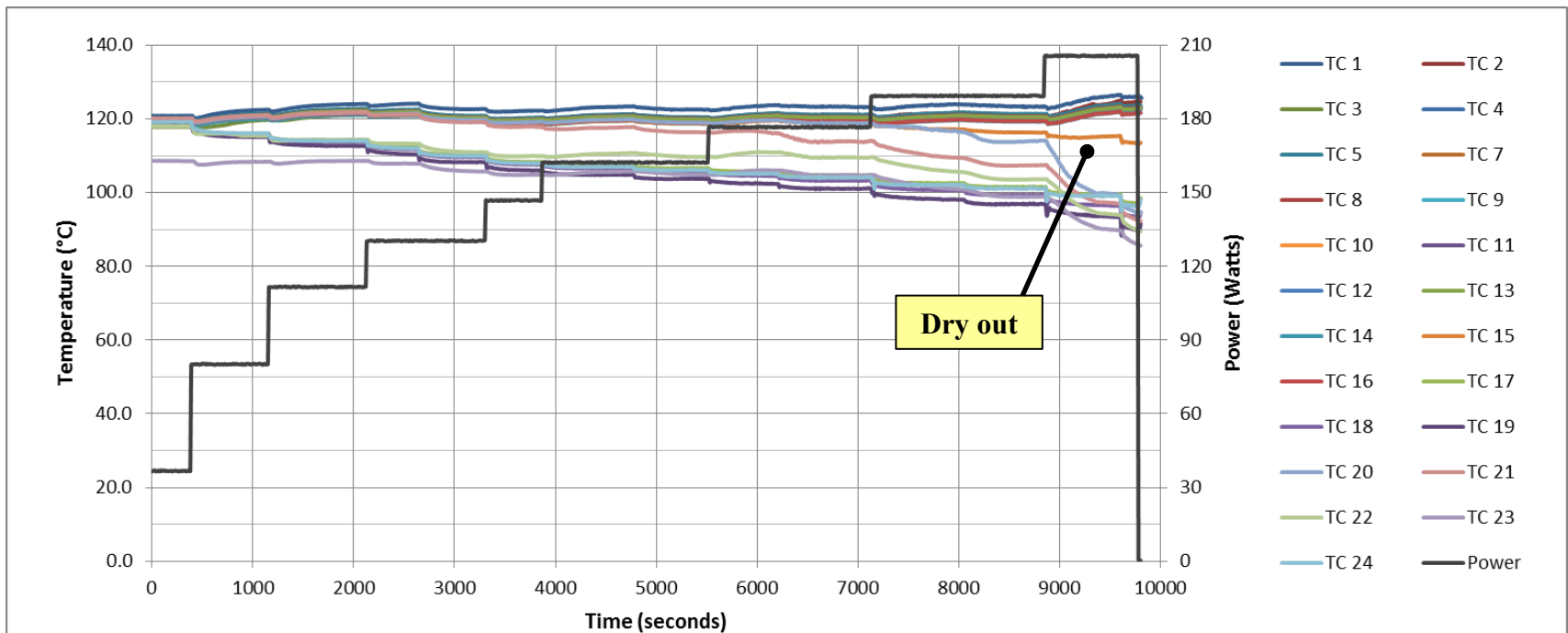


Freeze-Thaw Startup Test

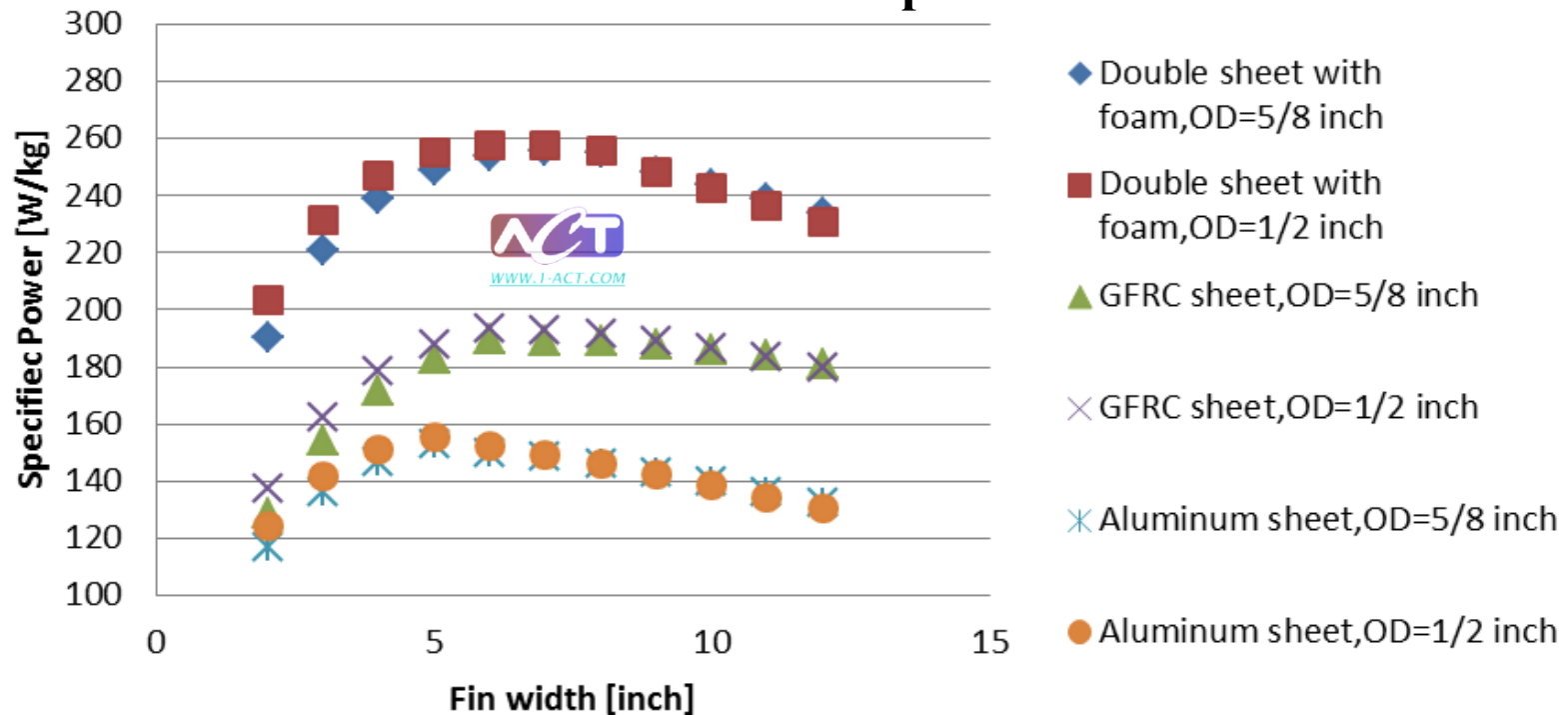
- Snapshot of temperature distribution at frozen and steady state



- **Initial performance tests showed ~130 Watt transport**
 - Does not meet requirement (250 Watt)
 - Monel screen was used in place of Titanium because of cost, but was not oxidized for proper wetting; therefore we suspect wetting angle is large, so capillary pumping is small
 - Performed a non-invasive oxidation procedure to treat the Monel screen
- **Performance test after oxidation showed 190 Watt transport**
 - Improvement, but still does not meet requirement (oxidation not sufficient)



Specific Power of 1.75m Radiator with 0.012" fin thickness for various HP envelope sizes



- The \uparrow W/kg, the \uparrow $q_{transport}$ and \downarrow mass
- Optimal fin width: ~6 inches

- Aluminum radiator is cheaper and more readily available than GFRC or double sheet with honeycomb panels and POCOfoam saddles
- S-Bond is a high temperature solder for Aluminum to Titanium
- Prototype **thermosyphon** radiator

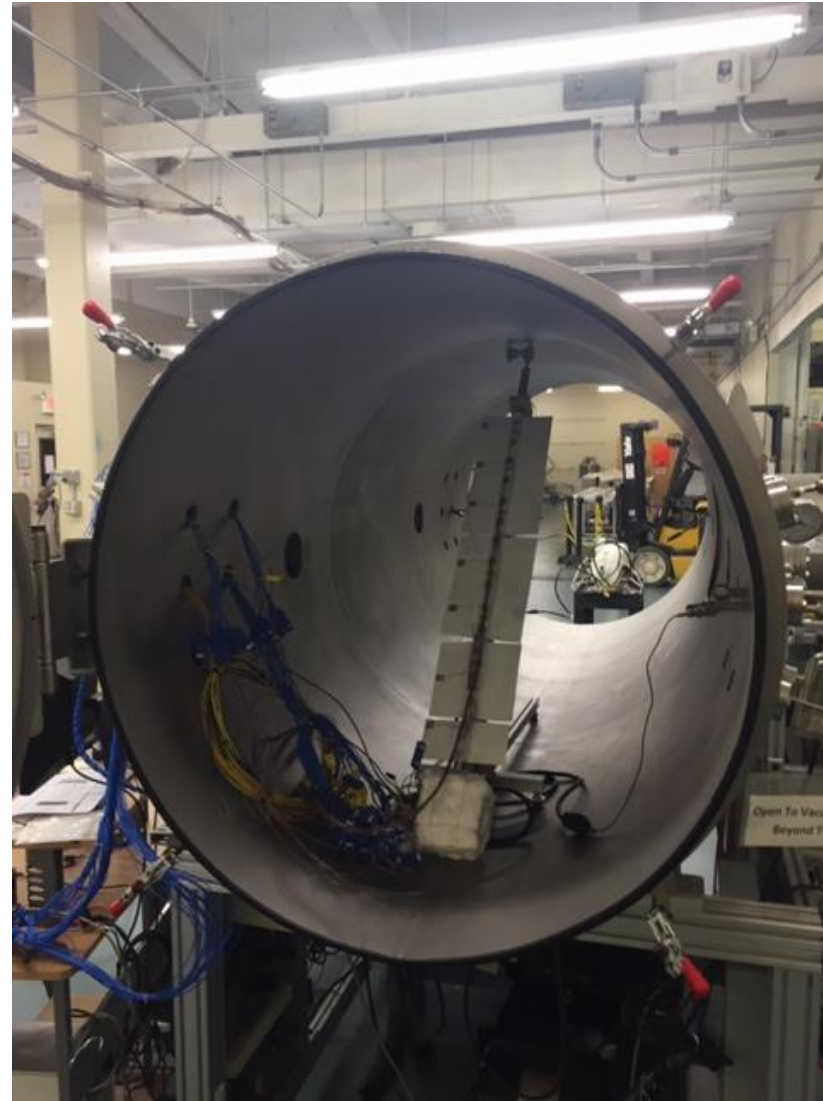
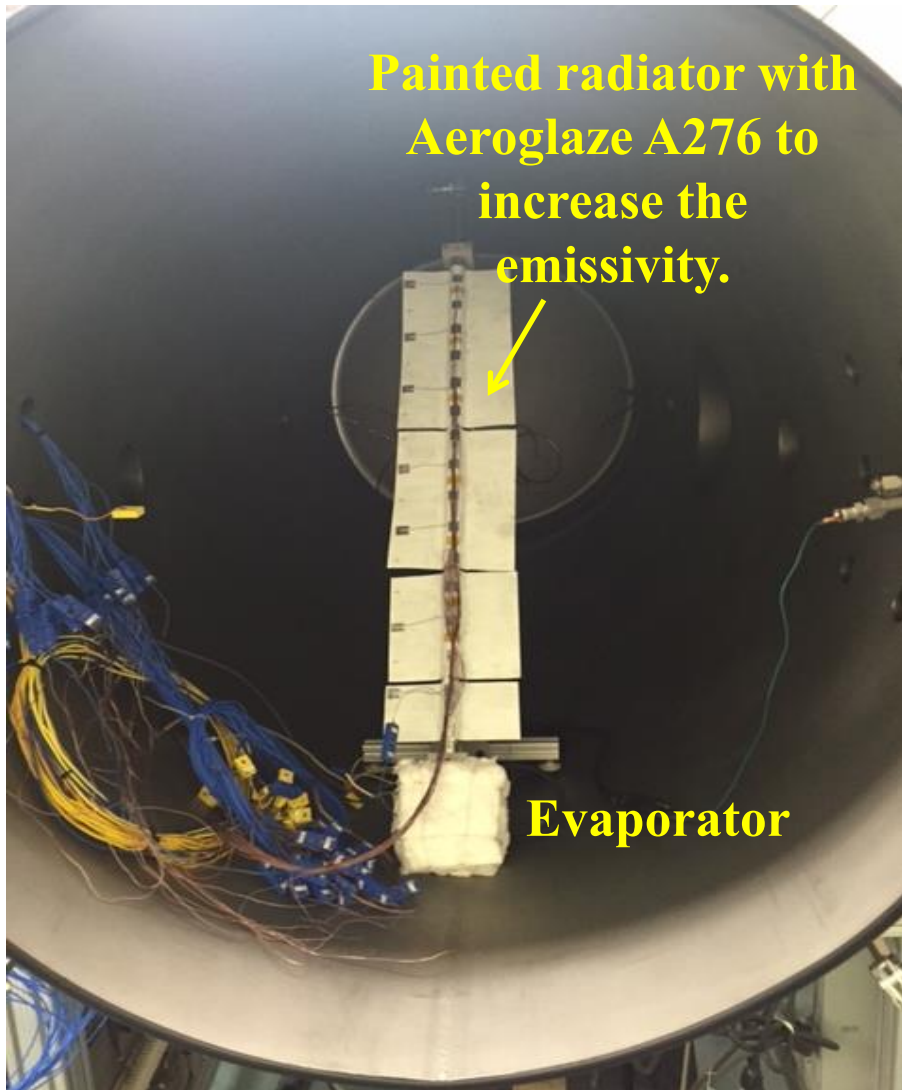
Top view

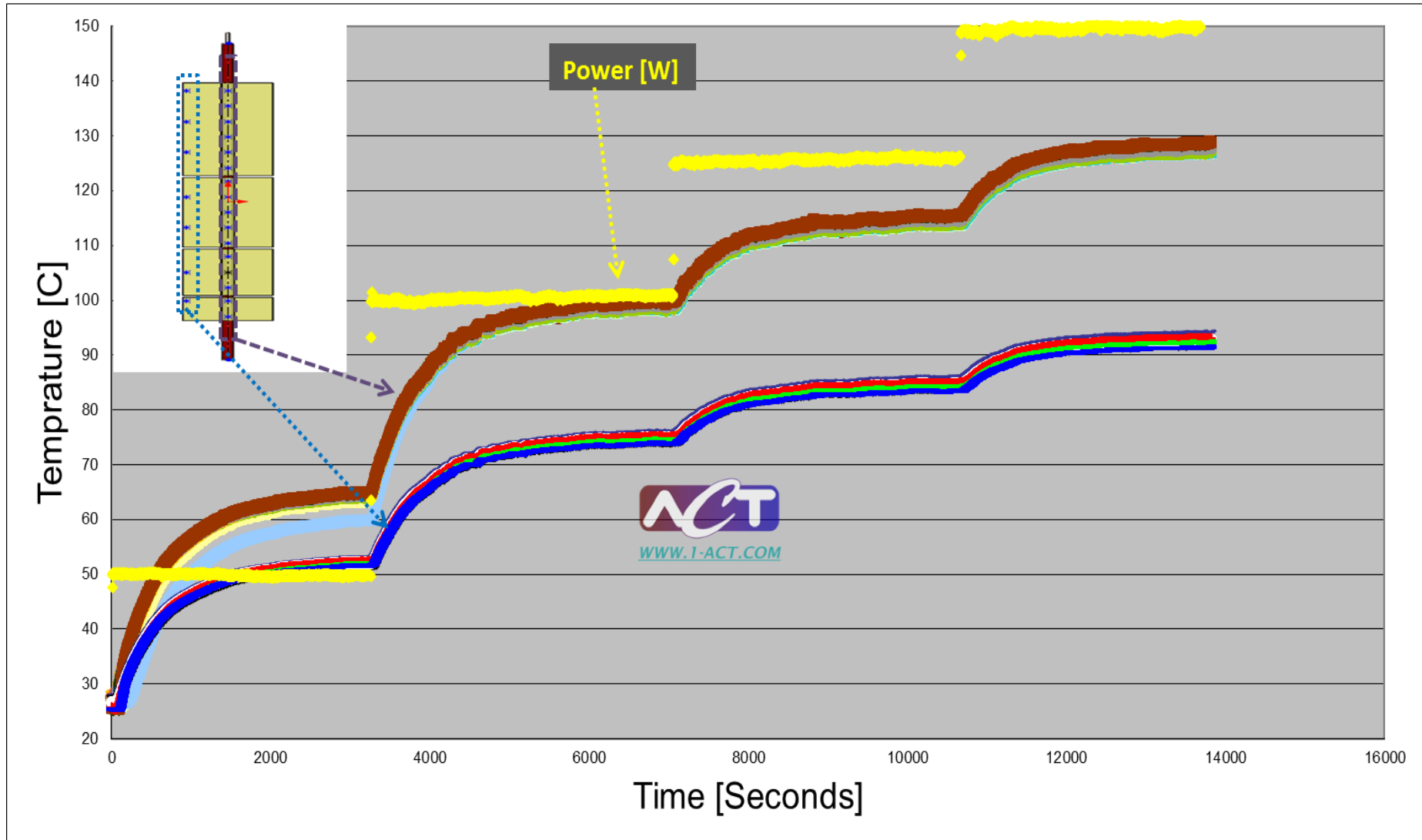


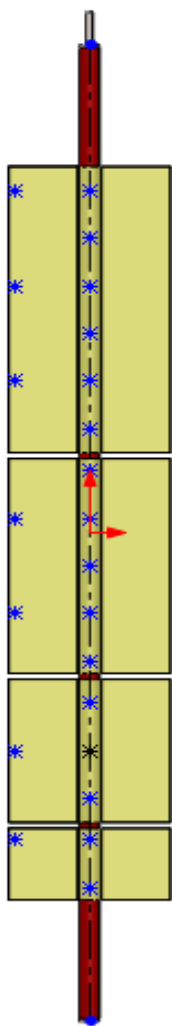
Bottom view



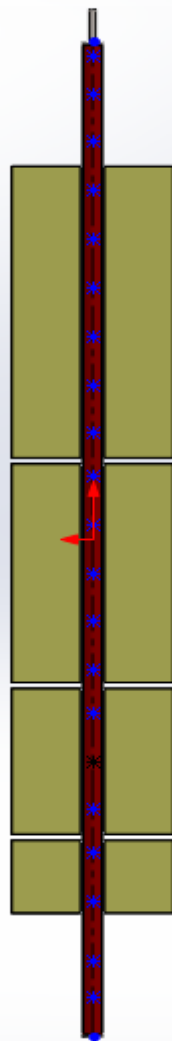
Testing in the Vacuum Chamber





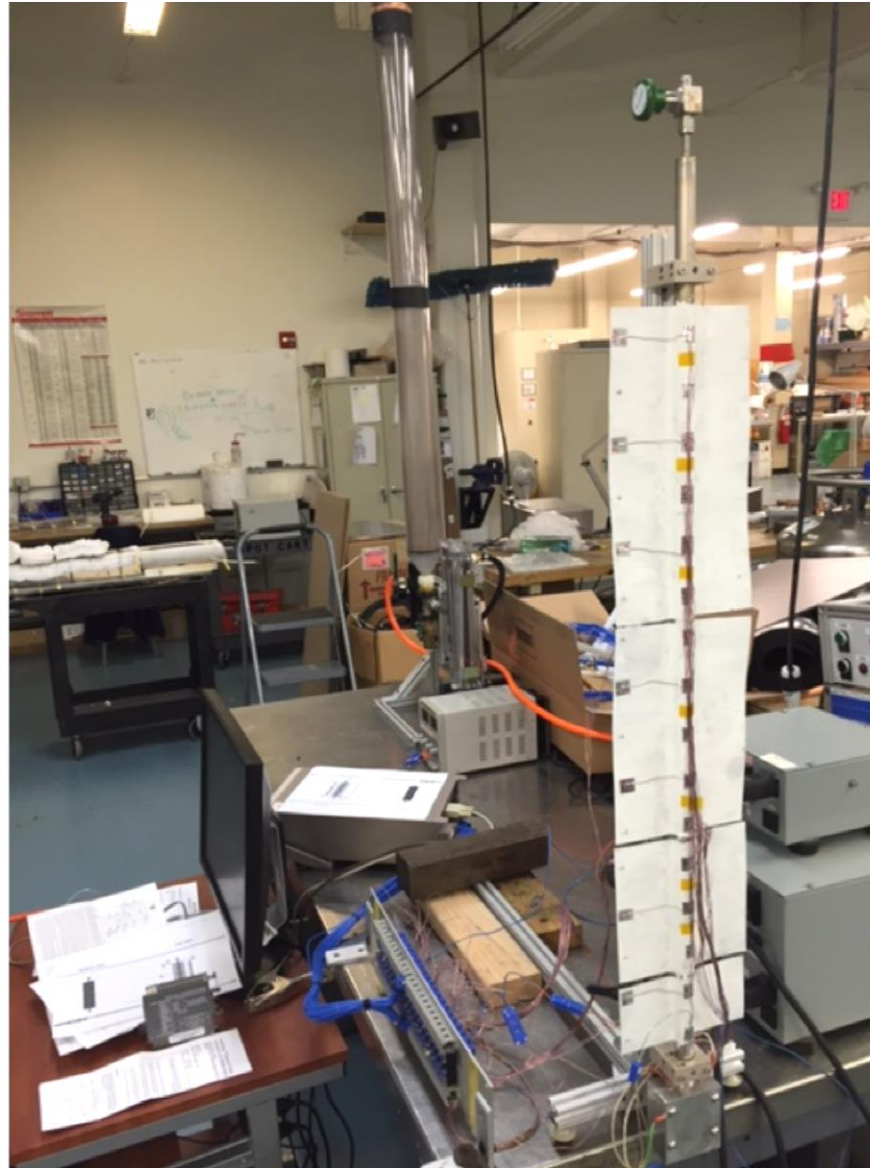


Top view

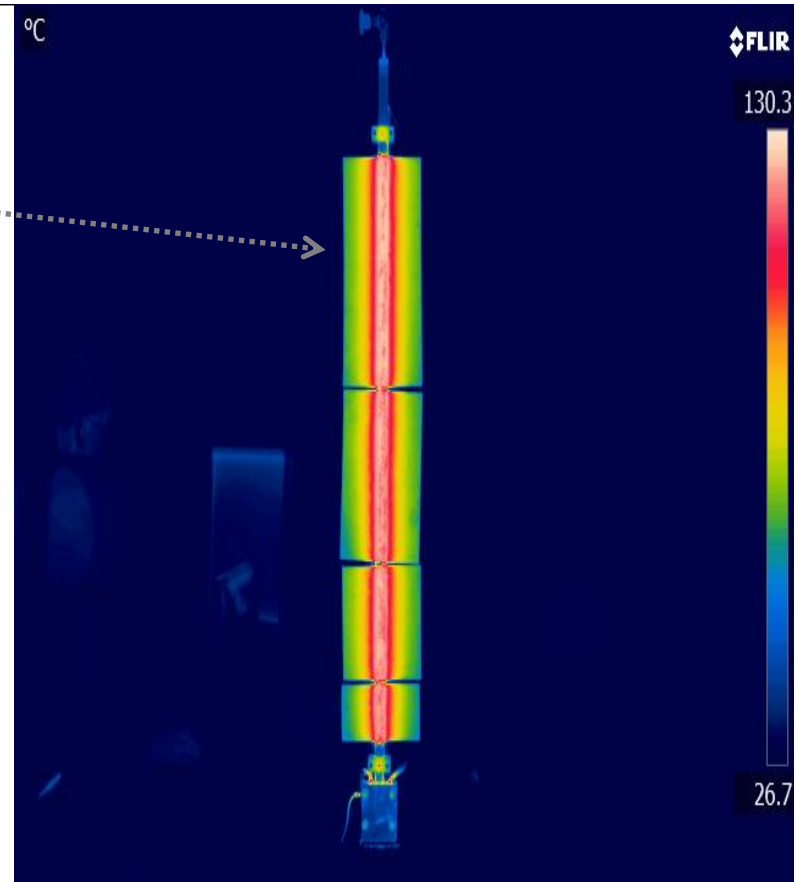
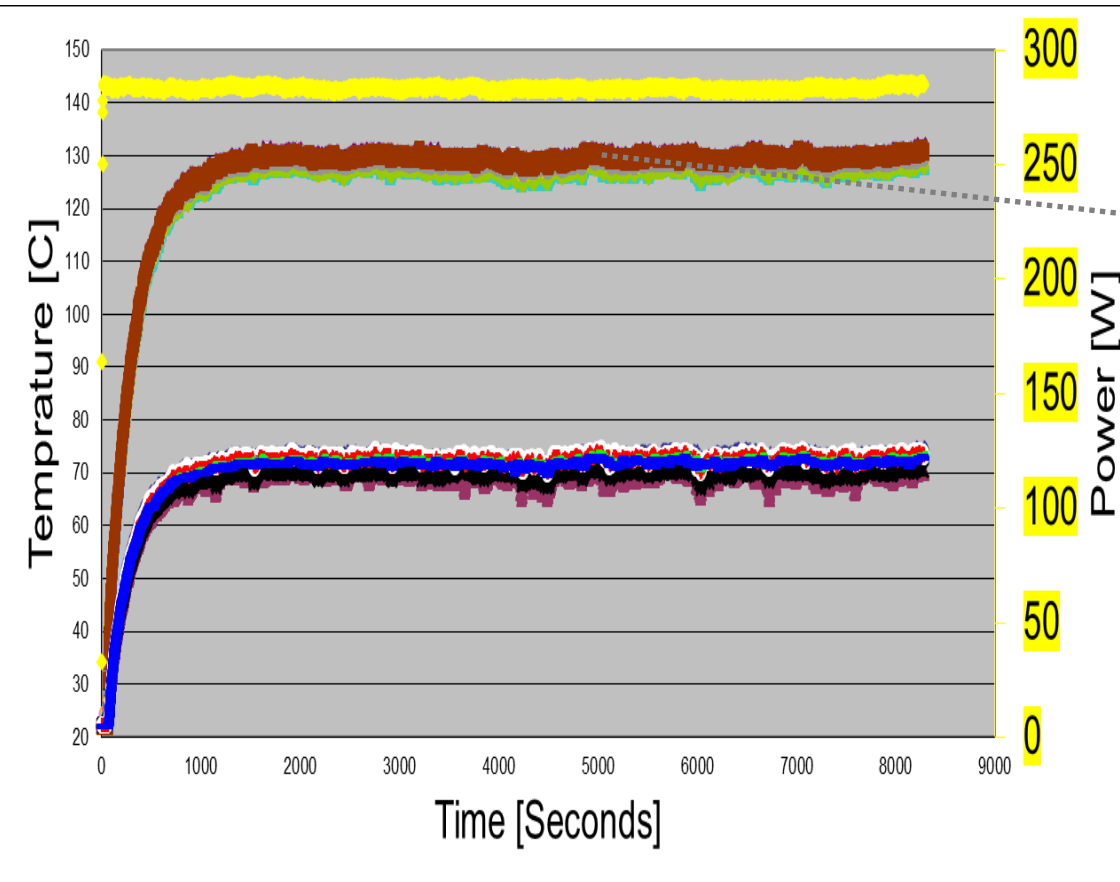


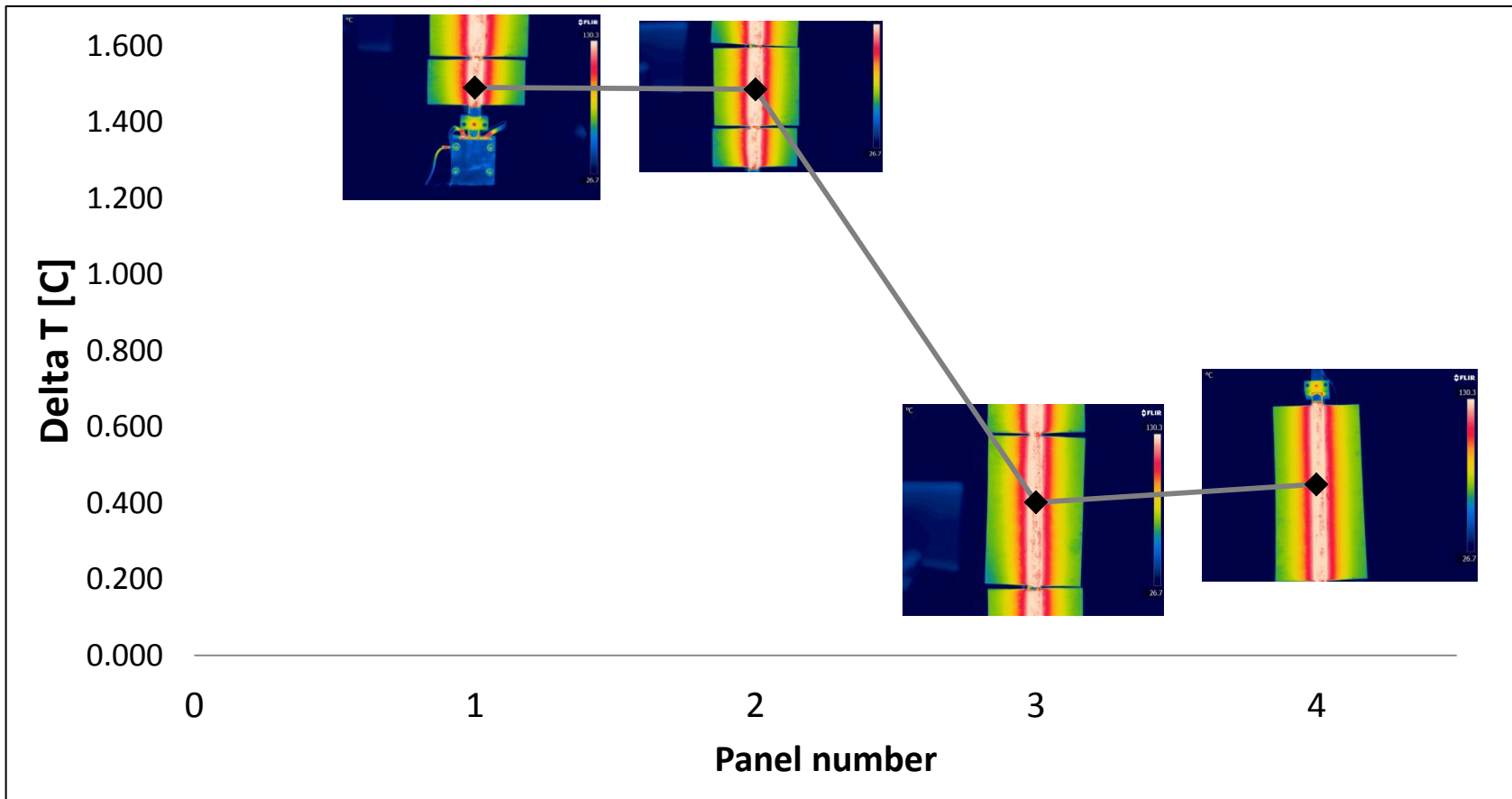
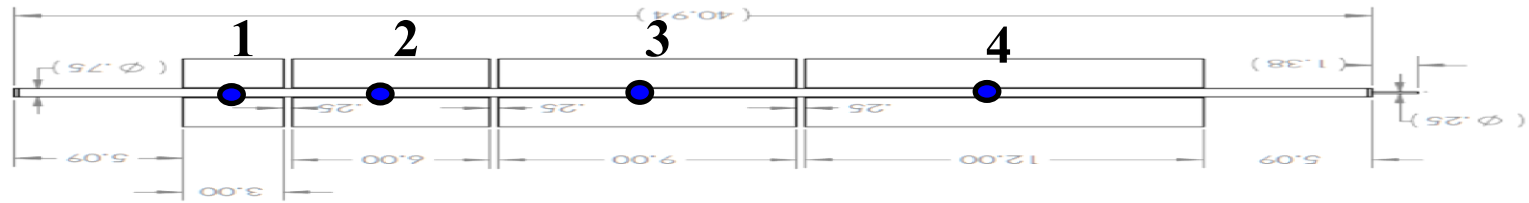
Bottom view

Fin		Titanium		Aluminum	
		13	126.72		
		12	126.85		
		11	126.76		
36	91.44	10	127.73	128.65	29
				128.52	28
35	92.40	9	128.01	128.06	27
		8	128.14	128.06	26
34	93.01			128.67	25
				127.69	24
		7	126.99	127.91	23
33	92.81			128.03	22
		6	126.77	128.14	21
32	92.17			128.16	20
				126.87	19
		5	127.66	126.20	18
31	93.50			127.70	17
				127.92	16
		4	127.63	127.40	15
30	93.13			127.41	14
		3	127.08		
		2	132.50		
		1	134.75		
Applied Power		Watts	150.51		



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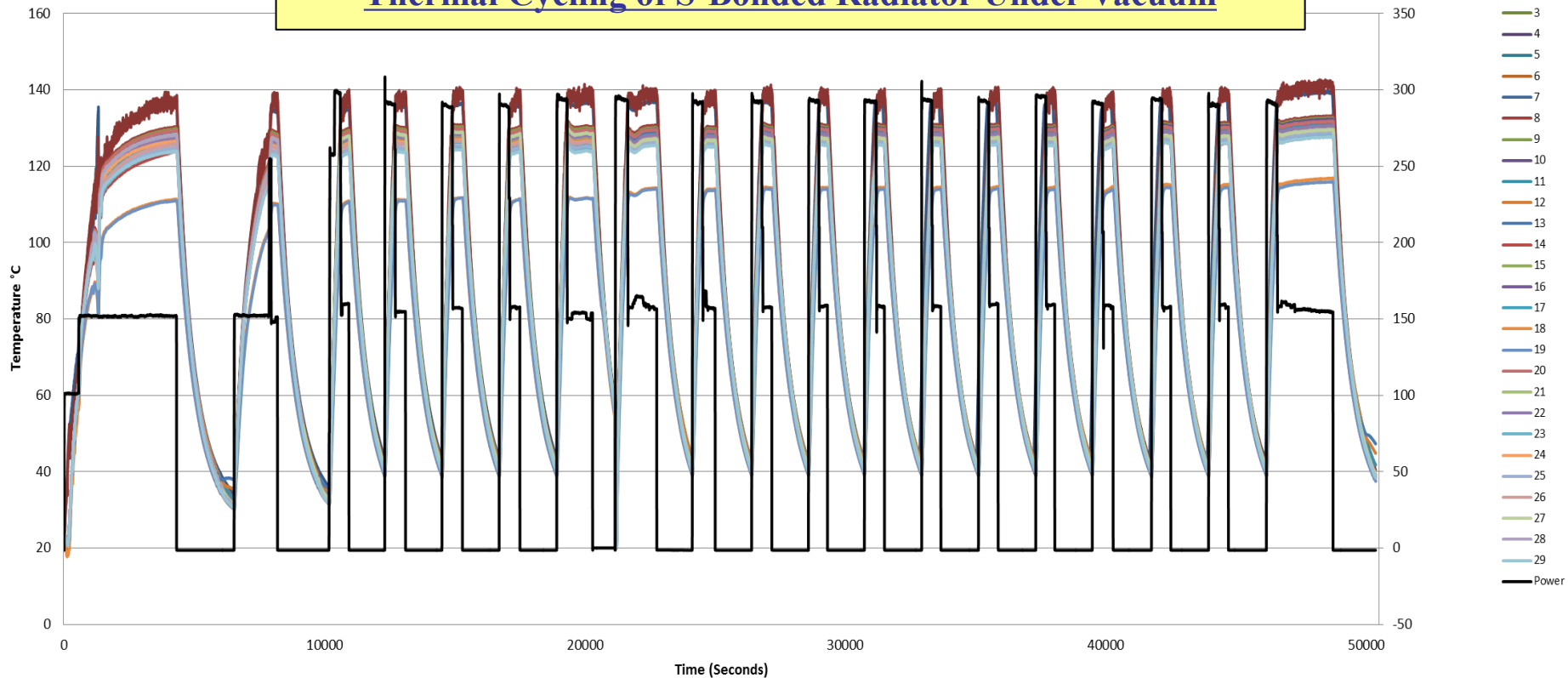




Radiator Thermal Cycle Testing

- Tested S-Bond for viability titanium - aluminum joint
 - Preliminary testing shows positive results
 - Low temperature gradient (0.3 C) across joint
 - 19 cycles in vacuum environment from 40 C to 140 C without degradation

Thermal Cycling of S-Bonded Radiator Under Vacuum



- **Key Results**

- Developed a working hybrid heat pipe with similar geometry to final configuration
- Demonstrated freeze-thaw capability of hybrid heat pipe
- Developed Aluminum radiator using S-Bond
- Validated radiator performance by testing in vacuum and ambient

- **Future Work**

- Revise evaporator design for better performance
- Integrate heat pipe and radiator thermal models to determine final configuration
- Fabricate and test 4 heat pipe radiator deliverables



Acknowledgements



- ◆ This program was sponsored by NASA Glenn Research Center under Contract Numbers NNX14CC27P and NNX15CC06C. Maxwell Briggs was the Technical Monitor
- ◆ We would like to thank Maxwell Briggs and Marc Gibson for their helpful suggestions



INNOVATIONS IN ACTION
The Thermal Management Experts

